

# The host galaxy of the short GRB 111117A at $z = 2.211^\star$

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## ABSTRACT

It is notoriously difficult to localize short  $\gamma$ -ray bursts (sGRBs) and their hosts to measure their redshifts. These measurements, however, are critical to constrain sGRB progenitors and delay time models. Here, we present spectroscopy of the host galaxy of GRB 111117A and measure its redshift to be  $z = 2.211$ . This makes GRB 111117A the most distant high-confidence short duration GRB detected to date. Our spectroscopic redshift supersedes a lower photometric redshift value for this burst previously estimated.

We use the spectroscopic redshift, as well as new imaging data to constrain the nature of the host galaxy and the physical parameters of the GRB. The rest-frame X-ray derived hydrogen column density, for example, is high compared to a complete sample of sGRBs and seems to follow the evolution with redshift as traced by the hosts of long GRBs (IGRBs). This is consistent with a proportion of the sGRB population originating in late-type galaxies, living in similar environments to that of IGRB hosts.

The host lies in the brighter end of the expected host brightness distribution at  $z = 2.211$ , and is actively forming stars. Using the host as a benchmark for redshift determination, we find that less than 55 per cent of all sGRB redshifts should be missed due to host faintness at  $z \sim 2$ . The high redshift of GRB 111117A is evidence against a lognormal delay-time model for sGRBs through the predicted redshift distribution of sGRBs, which is very sensitive to high- $z$  sGRBs.

From the age of the universe at the time of GRB explosion, an initial neutron star (NS) separation of  $a_0 < 3.2 R_\odot$  is required in the case where the progenitor is a circular pair of inspiralling NSs. This constraint excludes some of the longest formation channels for this burst.

**Key words.** Gamma-ray burst: individual: GRB 111117A —

## 1. Introduction

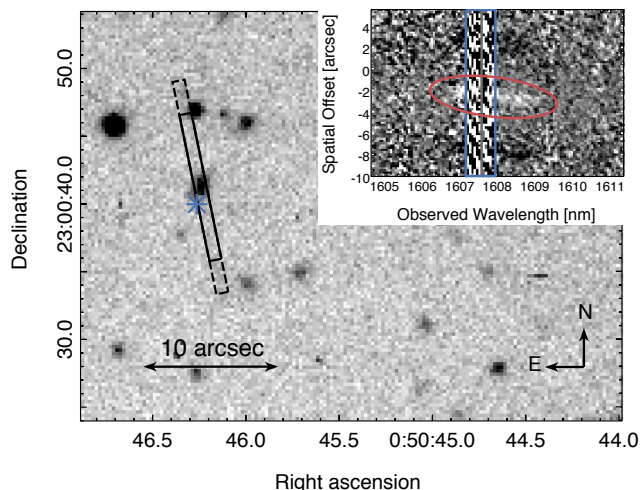
There is mounting evidence that short-duration  $\gamma$ -ray bursts come from the merger of NSs, either with another NS, or a black hole, due to their apparent association with kilonovae (Barnes & Kasen 2013, Tanvir et al. 2013, Yang et al. 2015, Jin et al. 2016, Rosswog et al. 2016). The absence of associated supernovae in deep searches (e.g. Hjorth et al. 2005b, Fox et al. 2005, Hjorth et al. 2005a) supports this idea and distinguishes the physical origin of sGRBs from their long-duration counterparts.

The host galaxies of sGRBs are diverse. They are more massive and less actively star-forming on average than IGRB hosts

(Fong et al. 2013), while in some cases, no host galaxy can be identified above detection threshold of deep follow-up observations (Berger 2010, Tunnicliffe et al. 2014). Together with their position within their hosts (Fong & Berger 2013), this suggests a progenitor system that can be very long-lived, and is associated with stellar mass rather than star-formation rate (SFR) (Berger 2014). The median redshift for sGRBs is  $z \sim 0.5$  (Berger 2014), and because most of these measurements come from the associated hosts, it is arguably biased towards lower redshifts.

The total lifetimes of NS binaries depends on their orbit, mass, spin, initial separations and subsequent inspiral times. The delay time from formation to explosion impacts the timing and distribution of the enrichment of the ISM with heavy  $r$ -process elements (van de Voort et al. 2014, Wallner et al. 2015, Ji et al.

<sup>\*</sup> Based on observations collected at the European Southern Observatory, Paranal, Chile, Program ID: 088.A-0051 and 091.D-0904.



**Fig. 1.** Imaging of the field of GRB 111117A with the X-shooter slit overlaid. The slit position represents 4 epochs of spectroscopic observations taken at similar position angles. The image is the FORS2 *R*-band image for which the photometry is shown in Fig. 3. The blue asterisk indicates the GRB position as derived from the *Chandra* observations in Sakamoto et al. (2013). The insert shows the 2D-image of the [O III]λ5007 emission line. The location of a bright skyline is marked by the blue box. The location of the emission line is indicated with the red ellipse. Because the host is observed in nodding-mode, negative images of the emission line appear on both sides in the spatial direction.

2016). Some limits can be calculated based on models of star-formation histories of, and the spatial distribution of sGRBs in, their host galaxies (Berger 2014). The most distant cosmological bursts, however, offer direct, hard limits on the coalescence time scales.

In this *Letter* we present a spectrum of the host galaxy of the short GRB 111117A ( $T_{90} = 0.46$  s) and measure its redshift to be  $z = 2.211$ . This value is significantly higher than the previously estimated redshift based on photometric studies (Margutti et al. 2012, Sakamoto et al. 2013). We present the GRB’s rest frame properties based on this new distance compared to previous analyses and revisit the host properties derived from the new solution to the spectral energy distribution (SED) fit. Throughout this *Letter* we use the  $\Lambda$ CDM cosmology parameters provided by Planck Collaboration et al. (2016) in which the universe is flat with  $H_0 = 67.7 \text{ km s}^{-1}$  and  $\Omega_m = 0.307$ . All magnitudes are given in the AB system.

## 2. Observations and results

### 2.1. Spectroscopic observations and analysis

Spectroscopic observations were carried out using the cross-dispersed echelle spectrograph, VLT/X-shooter (Vernet et al. 2011), at four separate epochs. The burst was observed 38 hours after the Burst Alert Telescope (BAT) trigger under ESO programme 088.A-0051 (PI: Fynbo) and again later under ESO programme 091.D-0904 (PI: Hjorth). X-shooter covers the wavelength range from 3000 Å to 24 800 Å (21 000 Å when the *K*-band blocking filter is used) across three spectroscopic arms. We carried out the bias-correction, flat-fielding, order tracing, wavelength calibration, rectification, and flux calibration using the VLT/X-shooter pipeline version 2.8.4 (Modigliani et al. 2010). The observations are combined and extracted using scripts de-

scribed in Selsing et al. 2017 (in prep.) and available online<sup>1</sup>. An overview of the spectroscopic observations is given in Table 1, and the slit position is shown in Fig. 1. We show the extracted spectrum in Fig. 3.

We determine a redshift of  $z = 2.211$  from the simultaneous detection of emission lines belonging to Ly $\alpha$ , [O II], H $\beta$ , [O III]λ5007, and H $\alpha$ . H $\beta$  is detected at low significance ( $\sim 3\sigma$ ). We show [O III]λ5007 in the insert in Fig. 1. H $\alpha$  is only visible in the first epoch due to the *K*-band blocking filter used for the remainder observations. The nebular lines exhibit a spatial extent of  $\sim 1''.5$  and show significant velocity structure along the slit. A drop in the continuum to the blue of the Ly $\alpha$  line further supports the inferred redshift.

Using the luminosity of H $\alpha$ , we can infer the star-formation rate (SFR) of a galaxy (Kennicutt 1998). At the redshift of the GRB host, H $\alpha$  is observed at 21 000 Å where the night sky is very bright. In addition, several bright sky-lines are superposed on the line, making an accurate estimate of the H $\alpha$ -flux difficult. We obtain a limit on the SFR by integrating the part of H $\alpha$  free of contamination and correcting for the missing flux using the line shape. After converting the Kennicutt (1998) relation to a Chabrier (2003) initial mass function using Madau & Dickinson (2014), we derive a limit of  $SFR > 7 M_\odot \text{ yr}^{-1}$ . From the SED-fit (Sect. 2.2), and the detection of Ly $\alpha$ , the host is constrained to contain very little or no dust, although the presence of Ly $\alpha$  does not exclude dust. Therefore we do not apply a dust-correction to the measured H $\alpha$  flux here.

### 2.2. Imaging observations and SED analysis

In addition to the spectroscopy presented above, we imaged the field of GRB 111117A in multiple broad-band filters using the VLT equipped with FORS2 (*gRIz* filters) and HAWK-I (*JHK<sub>s</sub>* filters), long after the burst faded. These new data are complemented by a re-analysis of some of the imaging used in Margutti et al. (2012) and Sakamoto et al. (2013) that are available to us (GTC *gri*-band, TNG *R*-band, and Gemini *z*-band). A log of the photometric observations and measured brightnesses is given in Table 2. Due to the optical darkness of this burst, there is likely no afterglow contamination on the measured photometry.

All data were reduced, analyzed and fitted in a similar manner as described in detail in Krühler et al. (2011) and, more recently, in Schulze et al. (2016). Briefly, we use our own Python and IRAF routines to perform a standard reduction which includes bias/flat-field correction, de-fringing (if necessary), sky-subtraction, and stacking of individual images. The photometry of the host was calibrated relative to field stars from the SDSS and 2MASS catalogs in the case of *grizJHK<sub>s</sub>* filters. We convert all magnitudes into the AB system, and correct for a Galactic foreground of  $E_{B-V} = 0.027$  mag.

The multi-color SED is fit by Bruzual & Charlot (2003) single stellar population models based on a Chabrier (2003) with initial mass function in *LePhare* (Ilbert et al. 2006), where the redshift is fixed to the spectroscopic value of  $z = 2.211$ . The best fit model is an unreddened galaxy template, and returns physical parameters of absolute magnitude ( $M_B = -22.0 \pm 0.1$  mag), stellar mass ( $\log(M_\star/M_\odot) = 9.9 \pm 0.2$ ), stellar population age ( $\tau = 0.5^{+0.5}_{-0.3}$  Gyr) and star-formation rate ( $SFR_{\text{SED}} = 11^{+9}_{-4} M_\odot \text{ yr}^{-1}$ ). We show the SED fit in Fig. 3.

Noteworthy is the discrepancy of our new VLT/FORS2 photometry and the re-analysis of the Gemini data to the *z*-band measurements of Margutti et al. (2012) and Sakamoto et al. (2013).

<sup>1</sup> [https://github.com/jselsing/XSGRB\\_reduction\\_scripts](https://github.com/jselsing/XSGRB_reduction_scripts)

Both of these authors report  $z$ -band photometry that is brighter by 0.8 mag to 1.0 mag compared to our value, where data taken in bluer filters are in excellent agreement. The large  $i - z$  color was mistakenly interpreted as a 4000 Å break driving the galaxy photometric redshift of the earlier works. Using the revised photometry from Table 2, the photometric redshift of the galaxy is  $z_{\text{phot}} = 2.04^{+0.19}_{-0.21}$ , consistent with the spectroscopic value at the  $1\sigma$  confidence level.

### 2.3. X-ray temporal and spectral analysis

We retrieved the automated data products provided by the *Swift*-XRT GRB repository<sup>2</sup> (Evans et al. 2009). The obtained spectrum is well described by an absorbed power-law model and the best-fit spectral parameters are a photon index of  $2.1 \pm 0.4$  and an intrinsic equivalent hydrogen column density  $N_{\text{H}}$  of  $2.4^{+2.4}_{-1.6} \times 10^{22} \text{ cm}^{-2}$  ( $z = 2.211$ ), assuming a solar abundance and a Galactic  $N_{\text{H}}$  in the burst direction of  $4.1 \times 10^{20} \text{ cm}^{-2}$  (Willingale et al. 2013).

## 3. Reinterpretation of the restframe properties

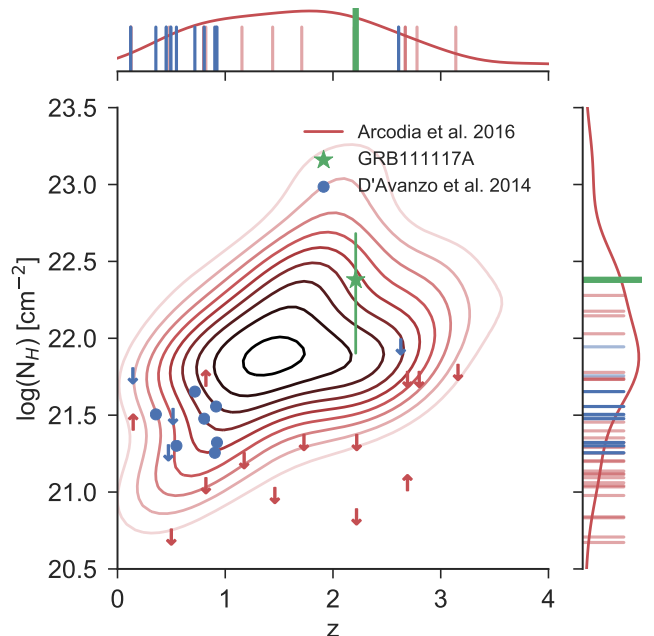
Because the projected distance does not change significantly between  $z = 1.3$  and  $z = 2.211$ , all conclusions of Margutti et al. (2012) and Sakamoto et al. (2013) relating to host offset are unaffected.

### 3.1. Classification

As already pointed out (Margutti et al. 2012, Sakamoto et al. 2013), GRB 111117A is securely classified as belonging to the short class of GRBs. Because the observed classification indicators,  $T_{90}$  and hardness ratio, do not depend strongly on redshift (Littlejohns et al. 2013), the updated redshift does not change this designation. Bromberg et al. (2013) investigated the degree to which the long and short population distributions overlap and quantified the certainty in the class membership. According to Bromberg et al. (2013), GRB 111117A has  $96^{+3}_{-5}$  percent probability of being a sGRB. Compared to the other two sGRB candidates at high redshift, GRB 060121 (de Ugarte Postigo et al. 2006, Levan et al. 2006) at  $1.7 \lesssim z \lesssim 4.5$  ( $17^{+14}_{-15}$  per cent) and GRB 090426 (Antonelli et al. 2009, Levesque et al. 2010, Thöne et al. 2011) at  $z = 2.609$  ( $10^{+15}_{-10}$  per cent), the certainty in class membership for GRB 111117A is much higher. This means that GRB 111117A happened when the universe was younger by 1.8 Gyr compared to any other non-collapsar GRB ever detected. This number is 3.2 Gyr for the next-highest spectroscopic redshift. This has implications for the  $r$ -process element enrichment timescale of the universe.

### 3.2. Restframe $N_{\text{H}}$

We show the recalculated  $N_{\text{H}}$  in Fig. 2 where we compare with the distributions of complete samples of both long and short GRBs. The IGRB sample is from Arcodia et al. (2016) and the sGRB sample is from D’Avanzo et al. (2014). 17 out of the 99 long bursts do not have measured redshifts, and likewise for 5 out of 16 in the short sample. Bursts without measured redshifts have been excluded for both groups. GRB 111117A occupies a unique position in Fig. 2 with the highest  $N_{\text{H}}$  of all short bursts. Additionally the upper limit at  $z = 2.609$  belongs to GRB 090426



**Fig. 2.** Rest frame, X-ray derived equivalent hydrogen column densities for GRB 111117A compared to complete samples of both long and short populations. The detections are replaced with contours for clarity and the limits are shown with arrows.

and does not belong in the short sample. The short sample, excluding GRB 111117A, is located at low redshifts ( $z < 1$ ) and is found to populate a similar column density environment to IGRBs at similar redshifts (D’Avanzo et al. 2014). The inferred hydrogen column density for GRB 111117A seems to follow the trend with increasing  $N_{\text{H}}$  as a function of redshift as found for the IGRB afterglows (Arcodia et al. 2016).

### 3.3. Host galaxy

As the majority of sGRBs (Fong et al. 2013), the host of GRB 111117A is a late-type galaxy and is entirely consistent in terms of stellar mass and stellar age with the general population of sGRB hosts ( $\langle M_{\star} \rangle = 10^{10.1} M_{\odot}$  and  $\langle \tau_{\star} \rangle = 0.3$  Gyr) (Leibler & Berger 2010). Being a late-type host, both the stellar mass and sSFR are entirely within the range expected for the hosts of sGRBs (Behroozi et al. 2014). The SFR is  $\sim 1$  order of magnitude higher than the typical SFR for sGRB host galaxies (Berger 2014) and more similar to the SFR found in the hosts of IGRBs at a corresponding redshift (Krühler et al. 2015). The high SFR is partly a selection effect, because a less star forming galaxy would exhibit weaker emission lines, thus making the redshift harder to determine. Additionally, it is natural to expect some evolution in the hosts of sGRBs with redshift as illustrated in Sect. 3.2.

## 4. Implications for the redshift distribution of sGRBs

A single sGRB at high redshift does little in terms of constraining the redshift distribution of sGRBs. In particular, other sGRB hosts could be missed because they are intrinsically fainter and thus this high- $z$  event is only detected due to the brightness of its host. Berger (2014) compiled a sample of sGRB host luminosities

<sup>2</sup> [http://www.swift.ac.uk/xrt\\_products/00507901](http://www.swift.ac.uk/xrt_products/00507901)



ties, normalized by the characteristic galaxy luminosity at their respective redshift,  $L_B/L_B^*$ . Out of the 39 hosts in the sample, 26 (66 per cent) have measured redshifts. To convert the SED-inferred  $M_B$  of GRB 111117A to  $L_B/L_B^*$ , we use the characteristic absolute  $B$ -band magnitude of the Schechter function for blue galaxies ( $U - V < 0.25$ ) in the redshift window  $2.0 \leq z \leq 2.5$  from Marchesini et al. (2007). For GRB 111117A, we obtain  $L_B/L_B^* = 1.2$ , which is brighter than 70 per cent of the hosts in Berger (2014) with measured  $L_B/L_B^*$ .

If we assume that we are able to obtain emission-line redshifts from hosts with  $R < 25$  mag (Krühler et al. 2012), then we would have missed around 30 per cent (8 out of 26 from the sample of Berger 2014 with measured  $L_B/L_B^*$ ), if they were at the redshift of GRB 111117A. Because the average SFR of galaxies hosting IGRBs is higher than for galaxies hosting sGRBs, the fraction of missed burst redshifts is likely higher although the cosmic SFR evolution could play a role in improving redshift determinability.

A fraction of the bursts missing redshift are host-less and is therefore likely at moderate redshifts (Tunncliffe et al. 2014), but should some of the remainder be at high redshift, the missed fraction will increase. If we assume that *all* the bursts that are missing redshifts in Berger (2014) are at high- $z$  and missed due to host faintness, 22 out of 39 hosts (55 per cent) would be missed at  $z = 2.211$ . This serves as an upper limit on the fraction of missed burst at high- $z$  and illustrates that we are likely *not* missing a large fraction of sGRBs redshift at  $z \approx 2$  due to host faintness.

The theoretical redshift distribution of sGRBs depends on the type of delay-time function used to model the progenitor system. The likelihood preferred lognormal time delay models investigated by Wanderman & Piran (2015) predict a sGRB rate at  $z = 2.211$ ,  $\sim$  two orders of magnitude lower compared to the peak rate at  $z = 0.9$ . According to Wanderman & Piran (2015), this preference depends critically on the absence of non-collapsar sGRBs at  $z \gtrsim 1.2$ . The redshift of GRB 111117A, on the other hand, is close to the expected peak in sGRB rate calculated using the power law delay time models (Behroozi et al. 2014, Wanderman & Piran 2015).

## 5. Constraints on progenitor separation

At  $z = 2.211$ , the age of the universe is 3 Gyr. If the progenitor systems of sGRBs are the merger of two NSs, this sets a hard upper limit to the coalescence timescale for such a system. In the absence of other mechanisms, the timescale of the orbital decay of the system is set by the energy loss due to gravitational waves, which in turn is set by the mass of the constituent compact objects and the separation of the two (Postnov & Yungelson 2014). If we assume that the formation timescale of the first galaxies is short compared to the time since the Big Bang (Richard et al. 2011), and if we assume a mass of  $1.4 M_\odot$  for each of the NSs at the time of system formation, this places a hard upper limit on the initial separation, of  $a_0 < 3.2 R_\odot$ .

In practice most NS-NS binaries will be eccentric at formation because of the SN natal kicks, and this can be quite a big effect on merger times, although eccentric systems normally circularise first. It could also be a BH-NS system, and as the merger time scales roughly as  $M^3$  the mass here almost as big an effect as the separation ( $a^4$ ).

Using the inferred stellar population age from our SED fit, then we obtain a (softer) limit on the initial separation of  $a_0 < 2.1 R_\odot$ . However, this does not account for the possibility there could be an underlying stellar population of older stars from a

previous star-formation epoch. The delay time between formation and explosion is well accommodated by the models of Belczynski et al. (2006), although the longest delay times are excluded. This is especially true given the late type nature of the host (O’Shaughnessy et al. 2008).

## 6. Conclusions

In this *Letter*, we have provided a revised, spectroscopic redshift measurement for the short GRB 111117A based on host galaxy emission lines setting it at  $z = 2.211$ . This value supersedes the previous photometric redshift of Margutti et al. (2012) and Sakamoto et al. (2013).

Using the new distance, the X-ray derived  $n_H$  towards GRB 111117A is the highest within a complete sample of sGRB hosts and is consistent with the  $n_H - z$  evolution traced by the hosts of IGRBs. The SFR of the host is in the upper end of the sGRB host SFR distribution and no dust is present. The high  $N_H$  is difficult to reconcile with the large projected host offset and the absence of dust. One possible explanation could be, that GRB 111117A is formed through the prompt channel of sGRBs (ref) and originates in a star forming region located in the outskirts of the host.

Although a single burst carries little leverage in terms of constraining the redshift distribution of sGRB, the high redshift of GRB 111117A needs to be accommodated in progenitor models. A lognormal delay time model predicts a very low volumetric density of bursts at  $z = 2.211$ , whereas a power law delay time model peaks near GRB 111117A. If more sGRBs are at similarly high redshifts, but are missed due to the faintness of their hosts, a lognormal delay time model will be disfavored. Compared to a sample of sGRB hosts, GRB 111117A is more luminous than 70 per cent of the sample with measured luminosities. Conservatively, for 55 per cent of the sGRB hosts, we would be unable to determine a redshift should they be at a similar redshift as GRB 111117A. This implies that we are *not* missing a large fraction of the sGRBs at  $z \sim 2$ .

Using the age of the universe at the time of explosion allows us to set constraints on the maximal separation between the engine constituents at the time of formation. We find that the maximal separation of two NSs at formation time is  $a_0 < 3.2 R_\odot$ , which excludes some of the formation channels with the longest timescales.

All data, code and calculation related to the paper along with the paper itself are available at <https://github.com/jselsing/GRB111117A>.

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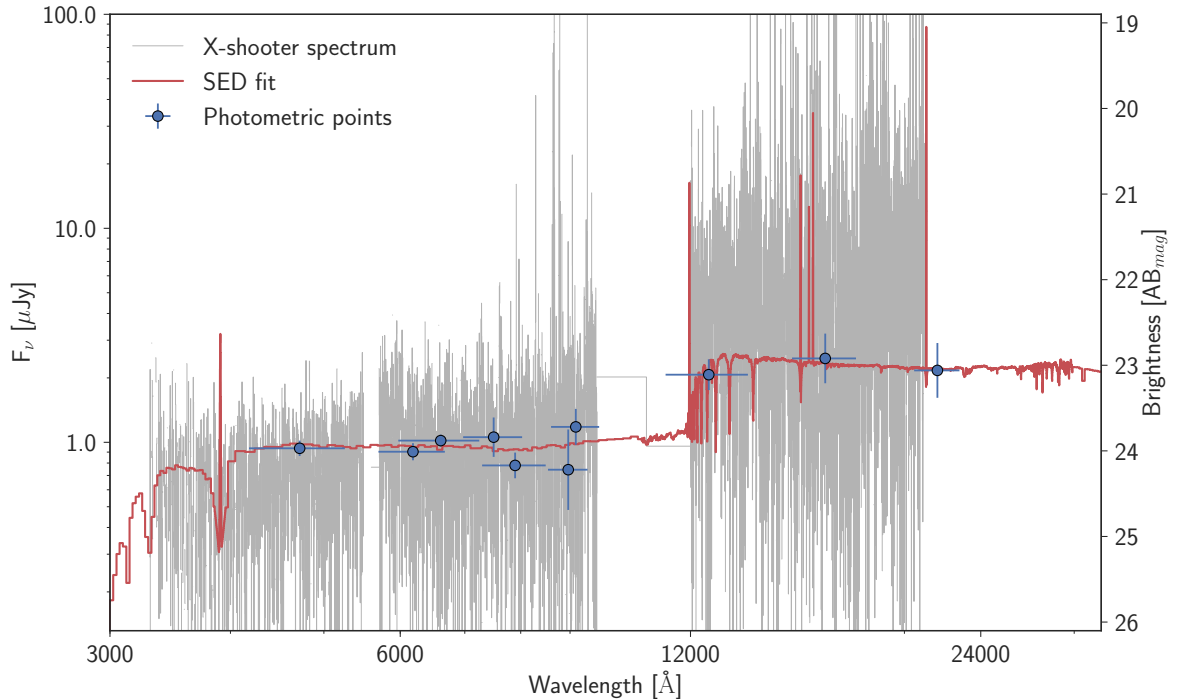
**Table 1.** Overview of the spectroscopic observations. JH in the slit width refers to observations where a K-band blocking filter has been used. The seeing is determined from the width of the spectral trace of a telluric standard star, taken close in time to the host observation. The spectral resolution,  $R$ , is measured from unresolved telluric absorption lines in the spectrum of the telluric standard star.

Obs. Date	Exposure time (s)			Slit width (arcsec)	Airmass	Seeing (arcsec)	R
	UVB	VIS	NIR				VIS/NIR
2011-11-19T01:33	2 × 2400	2 × 2400	8 × 600	1.0/1.0/0.9	1.49	0.75	11600/6700
2013-07-15T09:02	2 × 1200	2 × 1200	8 × 300	1.0/1.0/0.9JH	1.53	0.98	9600/8900
2013-08-03T07:37	2 × 1200	2 × 1200	8 × 300	1.0/1.0/0.9JH	1.55	0.85	11400/11300
2013-08-03T08:34	2 × 1200	2 × 1200	8 × 300	1.0/1.0/0.9JH	1.49	0.85	11400/11300

**Table 2.** Overview of the photometric observations.

Obs. Date	Exptime	Telescope/Instrument	Filter	Airmass	Image Quality	Host Brightness <sup>a</sup>
	ks					
					(arcsec)	(mag <sub>AB</sub> )
2013-08-30T07:43	1.45	VLT/FORS2	<i>g</i>	1.55	0.99	24.08 ± 0.09
2011-11-17T20:07	0.80	GTC/OSIRIS	<i>g</i>	1.15	1.67	24.13 ± 0.09
2011-11-17T20:07	1.20	GTC/OSIRIS	<i>r</i>	1.11	1.50	23.93 ± 0.08
2013-07-17T08:37	1.45	VLT/FORS2	<i>R</i>	1.56	0.74	23.95 ± 0.06
2011-11-28T21:10	3.60	TNG/DOLORES	<i>R</i>	1.01	1.08	23.96 ± 0.13
2011-11-17T20:07	0.36	GTC/OSIRIS	<i>i</i>	1.08	1.50	23.89 ± 0.23
2013-08-03T09:23	1.35	VLT/FORS2	<i>I</i>	1.54	0.93	24.22 ± 0.15
2011-11-28T06:14	1.80	Gemini/GMOS-N	<i>z</i>	1.01	0.84	24.24 ± 0.47
2013-07-13T09:33	1.08	VLT/FORS2	<i>z</i>	1.49	0.63	23.76 ± 0.21
2013-06-24T09:14	1.98	VLT/HAWK-I	<i>J</i>	1.70	0.63	23.13 ± 0.18
2013-06-27T09:21	1.68	VLT/HAWK-I	<i>H</i>	1.63	0.91	22.94 ± 0.29
2013-06-28T09:14	1.92	VLT/HAWK-I	<i>K<sub>s</sub></i>	1.65	0.76	23.07 ± 0.32

**Notes.** <sup>(a)</sup> All magnitudes are given in the AB system and are not corrected for the expected Galactic foreground extinction corresponding to a reddening of  $E_{B-V} = 0.027$  mag. (Thomas, Can you help with the reference for the data which are not ours?)



**Fig. 3.** SED fit showing the best-fit SED to the derived photometry. The detection of Ly $\alpha$  is predicted from the SED fit and confirmed by the spectroscopic observations. Overplotted in grey is the observed spectrum. The reason for the spectral gaps at 5500 Å and 10000 Å is from the merging of the arms.